SDR-Based Experiments for LTE-LAA Based Coexistence Systems with Improved Design

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***Abstract*— To enhance spectrum efficiency in next generation heterogeneous wireless systems, it is important to improve shared spectrum usage between unlicensed long-term evolution (LTE) systems, such as the license-assisted access (LAA), and legacy systems, such as wireless local area networks (WLANs). LTE-LAA uses listen-before-talk (LBT) schemes to enhance coexistence performance. However, available LAA-LBT schemes may incur several problems, such as a slot-jamming effect and a significant slot boundary tracking error, leading to degraded performance. In this paper, we develop an LBT scheme with improved design and software-defined radio (SDR)-based experimental procedure for a performance validation. We program the improved LBT algorithm in the SDR field-programmable gate array (FPGA), and compare the results with the original LBT algorithm. This work also presents an automated testing technique and new SDR functions that modify the LAA parameters in realtime (such as backoff idle slot durations). The experiment results confirm the predicted slot-jamming effect, and show that our improved design enhances LAA throughput. These results provide not only a more robust LAA-LBT design, but also a new method of SDR programming and testing, and insight into the coexistence performance of heterogeneous systems.**

Index Terms: Coexistence; FPGA programming; LTE-LAA; SDR experiments; Test automation; WLAN.

I. Introduction

Experimental design and evaluation are critical for performance validation of spectrum sharing techniques between long-term evolution license-assisted access (LTE-LAA) [1]–[6], [11] systems and incumbent systems, such as IEEE 802.11 wireless local area networks (WLANs). To support LTE system development and coexistence, software-defined radio (SDR) or commercial off-the-shelf (COTS)-based experimental methods have become popular, and various SDR test platforms are reported in [3], [7]–[9], [12].

The 3rd Generation Partnership Project (3GPP) LAA has defined four categories of listen-before-talk (LBT) schemes [1], [2] to improve coexistence with legacy systems. In LAA-based coexistence scenarios, LAA nodes may have a larger backoff slot duration than the WLAN counterpart. In [1], [2], LAA uses an extended clear channel assessment (eCCA) slot in the transmission backoff process. The eCCA duration is flexible, and may be 9 μs to 20 μs, or larger. The WLAN backoff slot duration is 9 μs (which includes CCA time) for several popular physical layer specifications [13]. Various coexistence settings based on LTE-LAA and WLAN transmissions have been evaluated, and laboratory and field test results are reported in [1]–[3], [12]. In particular, SDR devices were used in LAA and WLAN coexistence testing in [12]. However, none of these experimental results report the effect of heterogeneous LAA and WLAN idle slot durations on coexistence performance. In [17], we study the effect of heterogeneous idle slot duration and point out a slot-jamming (SJ) effect of WLAN nodes against LAA nodes in the transmissions backoff process. An anti-SJ-LBT scheme is proposed and its performance is analyzed and verified through computer simulation. Yet, experimental validation of the slot-jamming effect and its mitigation was still absent.

In an LAA transmission cycle, the time slots are divided into idle (backoff), transmission, channel-busy slots, etc. The slot-tracking in different transmission links need to align to maintain a satisfactory performance. In practice, synchronism (or near-synchronism) of slot boundaries has been assumed in the majority of system design, analysis and optimization results [1], [2], [14]–[20], though very often not explicitly discussed. However, the tracking of slot boundaries, such as in the instant when the channel switches from busy to idle, is a nontrivial issue. The LBT process defined in [1], [2] uses an initial CCA (iCCA) duration or a deferred extended CCA (DeCCA) duration to track this channel state change. The iCCA and DeCCA durations are typically suggested to be equal to the WLAN distributed coordination function interframe space (DIFS) duration, which is 34 μs for the IEEE 802.11a, 802.11n and 802.11ac specifications in the 5 GHz industrial, scientific, and medical (ISM) band [13]. To search for the instant that the channel turns from busy to idle, the LBT uses DeCCA duration as search step size for channel status tracking. However, since the DeCCA duration is much larger than the WLAN backoff idle slot duration, the original LBT design may lead to a significant slot-tracking error. Unsatisfactory slot-tracking accuracy can cause increased transmission collisions and reduced throughput. To our knowledge, the effect of this type of slot boundary tracking error has not been investigated in the literature of LAA-based coexistence systems. Experiment-based study and countermeasure design are important to address this problem.

In this paper, we address the SJ and the slot-tracking error problems in the original LBT process, develop an improved LBT scheme with anti-SJ and subslot-tracking features, and

Certain commercial equipment, instruments, or software are identified in this paper in order to adequately specify the experimentation procedure. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the software or equipment identified are necessarily the best available for the purpose.

implement SDR-based experimental validation. In [3], [7]–[9], [12], the capability of changing LAA LBT parameters in realtime for automated testing was neither discussed nor demonstrated. We note that there is a significant technical gap that needs to be bridged to allow flexible system parameter updates in realtime.

For this purpose, we program the improved LAA LBT function and WLAN functions, based on major modifications of available SDR software related to [12]. We implement SDR field-programmable gate array (FPGA) programming to allow flexible LAA LBT functions, where iCCA and eCCA slot durations can be modified in realtime. We also add user datagram protocol (UDP)-based communication functions to switch parameters and data between the host code and SDR-control codes. Then, we implement conducted tests assuming an additive white Gaussian noise (AWGN) channel in the LAA link, the WLAN link, and the LAA-WLAN mutual interference link.

The contributions and novelty of this paper are summarized as follows:

- We develop an improved LBT method to reduce the slot-jamming effect and slot-tracking error. This scheme is compatible with the existing 3GPP LAA LBT framework.
- We develop an FPGA programming method which implements our new LBT algorithm, and allows the updating of many LAA LBT parameters in realtime. This also includes a test-automation method between computer and SDR devices.
- Experimental results confirm the SJ effect, verify our analysis of the anti-SJ-LBT scheme in [17], and demonstrate enhanced throughput performance of the new LBT method relative to the original LBT.

These results address critical problems of LBT SJ effect and slot boundary alignment (tracking) error in system coexistence, and provide a countermeasure scheme. They also provide new SDR programming and demonstrate the capability to implement automated testing of coexisting systems.

II. System Model and Improved Design

Our testing scenario supposes that LTE-LAA nodes utilize unlicensed spectrum in the downlink and share it with incumbent WLAN nodes. The LTE-LAA system uses LBT to track channel status and makes backoff or transmission decisions. Refer to Fig. 1. After the transmission opportunity (TXOP) of an active link (say, a WLAN link) is completed, the transmission node starts the DIFS, followed by random backoff slots with slot duration of 9 μs. Here, for the sake of brevity we do not show the short interframe space (SIFS) and acknowledgement (ACK) signal durations. Note that the active link may also be an LAA link.

Suppose that there are three LAA nodes listening to the channel. To facilitate smooth coexistence, we assume that $T_{\text{DIFS}} = T_{\text{Defer}}$, where T_{DIFS} and T_{Defer} are WLAN DIFS and LAA deferred eCCA durations, respectively. Ideally, after the transmission of the WLAN link is completed, all the listening nodes would immediately start the DeCCA period.

The first link has perfect slot alignment with the WLAN link, and starts the eCCA slot synchronously with the WLAN

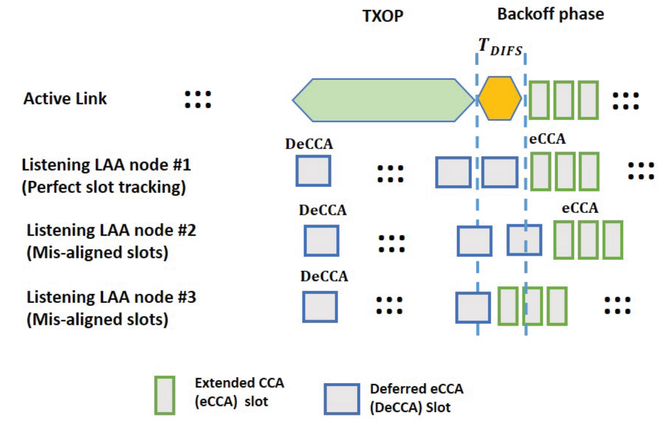

Fig. 1: The iCCA (or DeCCA) slot-tracking errors in the original LAA-LBT process.

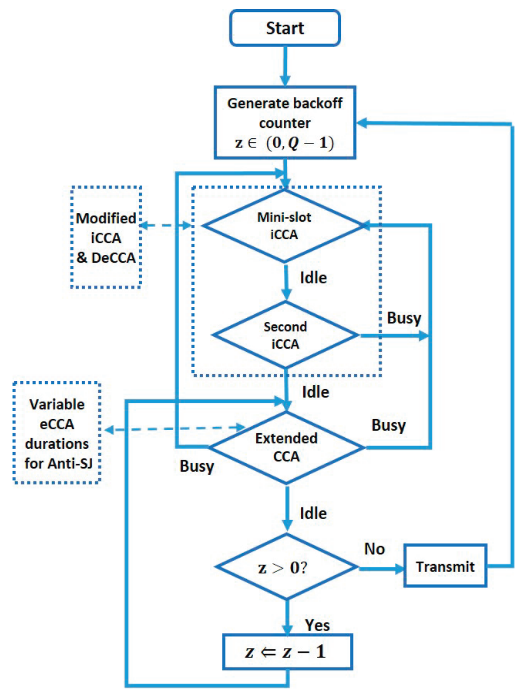

Fig. 2: An improved LAA-LBT scheme that reduces slot-tracking errors and the slot-jamming effect.

link. However, the second and third LAA nodes have major slot-tracking errors with respect to the WLAN link, so that node #2 starts the backoff count-down too late, and node #3 starts it too early.

We explain this phenomenon next. Based on the LBT process in [1], [2], during the channel busy time, the LAA node freezes its backoff process for a DeCCA period (which could be 34 μs as a default value). The energy detection (ED) output of each DeCCA duration at each LAA node is compared with a threshold to declare the channel busy or idle. After the channel status changes from busy to idle, the TXOP stop instant can lie in any range in a DeCCA window with duration 34 μs. This inherently causes a slot boundary alignment error in the range $(-17, 17)$ μs, or larger. Another weakness of this design is the sensitivity to the ED threshold setting. A low ED threshold may cause the DeCCA slot to be declared as channel-busy, and the LAA node will continue with one additional DeCCA slot, as shown for LAA node #2. A high ED threshold may cause the DeCCA slot be declared as channel-idle, and the LAA node will start the eCCA slot too early, as shown for LAA node #3. In a WLAN network, WLAN nodes may use a network allocation vector (NAV) in the packet header to determine the precise time that a transmission stops. However, we are not aware of an LAA specification that provides a method similar to the NAV for the LAA nodes to track the precise stop time of WLAN transmissions. Thus, the slot boundary tracking error becomes a significant issue in LAA and WLAN coexistence cases.

To address this problem, we propose a modified LBT process with subslot-tracking shown in Fig. 2. We merge the iCCA and DeCCA slots of the LBT for convenience, similar to that in [2]. As proposed in [16], we switched the order of blocks "Extended CCA" and "$z > 0$?" to remove the channel access priority of an LAA node, which just finished a successful transmission. Compared to available LBT schemes, such as those in [1], [2], [16], in Fig. 2 we split the iCCA/DeCCA slot into two sections, namely, "mini-slot iCCA" and "second iCCA" (where the word "DeCCA" is suppressed for convenience of notation). The "mini-slot iCCA" senses the channel with a much shorter duration than a regular iCCA/DeCCA slot, searching for the precise instant when a TXOP is over. Its purpose is to achieve precise slot boundary alignment. When the sensed signal power (or energy) exceeds the ED threshold (channel busy), the mini-slot iCCA is repeated until the channel is declared idle. When the ED result indicates an idle channel, the LBT process moves to the second iCCA sub-slot and senses for a larger time window. The purpose of this part is to be compatible with WLAN DIFS duration. Note that the sum duration of the "mini-slot iCCA" and "second iCCA" in Fig. 2 can be set equal to T_{DIFS} (34 μs), or any iCCA/DeCCA duration specified by LAA network designers.

This improved design may significantly reduce slot-tracking errors. Assuming that channel sensing in the "mini-slot iCCA" is reliable, the slot-tracking error is now bounded by the duration of the mini-slot iCCA (for example, 4 μs), instead of the regular DeCCA duration. This design is compatible with available 3GPP LBT design procedures, because it only involves a change of internal functions in the iCCA and DeCCA blocks. We programmed this method in FPGA code and loaded it onto SDR devices for verification.

Additionally, we experimentally study the impact of LBT SJ effect and the anti-SJ design. We define δ_L and δ_W as the backoff idle slot durations for LAA and WLAN systems, respectively. In [1], [2], the LBT backoff idle slot is called the LBT eCCA slot, with a flexible duration δ_L that can range from 9 μs to 20 μs, or larger. For several popular physical layer specifications [13] in the 5 GHz ISM band, the WLAN backoff slot duration is set to $\delta_W = 9$ μs. Our recent work [17] shows that as the ratio $N_s = \delta_L/\delta_W$ increases, there is an increasing chance the WLAN nodes jam the transmission opportunity of LAA nodes. We call this effect "slot jamming", where the LAA throughput decreases and WLAN throughput increases as N_s increases. We propose an anti-SJ-LBT in [17], which uses a variable eCCA duration based on channel status to enhance LAA transmission opportunity. This feature is shown in Fig. 2. Note that the original LBT uses a fixed eCCA duration, and we call it SJ-LBT in this paper.

III. Experimental Setup

Figure 3 shows a block diagram of the conducted measurement setup. A photo of part of this setup is shown in Fig. 4. The goal of this setup is to experimentally examine the slot-jamming and slot-tracking error effects, and the performance of the improved LBT design.

The software structure is shown in Fig. 5, which consists of host programming and SDR FPGA target programming. The host code runs on the computer, and includes a control interface. The control interface code that we programmed sends parameters to commercial LAA and WLAN codes via one set of UDP ports, reads test results via another set of UDP ports, and saves the results to data files of pre-specified formats on the computer hard drive for record and analysis. On the host computer two software projects run simultaneously and control the two SDR units, respectively. Two SDR devices emulate an LTE-LAA link and an WLAN link, respectively, or two LAA links. The communication channels were implemented with power combiner and splitter, and are AWGN channels, as shown in Fig. 3.

The first SDR device implements some LTE-LAA functions. The RF loopback mode was used: the eNode B (eNB, or base station) transmitted data to the user equipment (UE) via the RF ports and cable connections (downlink only), and did not receive any data from the UE via the RF channel (uplink). Some necessary handshaking signals in the uplink and synchronization functions are implemented internally on the FPGA, because the FPGA on a single SDR device emulates both eNB and UE functions.

The LTE-LAA code used on the SDR was a commercial implementation that we modified for use in these experiments. Several significant modifications to this commercial software included: implementation of new LBT functions, ability to adjust the LBT parameters in realtime, addition of a customized channel reservation signal (CRS) to mitigate LAA signal generation and transmission delay, and the addition of an automated testing ability.

The commercial FPGA code we used included an original LBT function but it was modified to add the improved LBT scheme with subslot-tracking and anti-SJ functions. The original DeCCA (or iCCA) state is split into two sub-states with duration of 4 μs and 30 μs, respectively. The state transitions among many LBT states are updated in FPGA, such as eCCA, mini-slot iCCA, iCCA, DeCCA, counter reduction, and transmission. Also, to implement the anti-SJ-LBT, the eCCA duration on FPGA is updated in realtime based on channel sensing results.

The ability to change the LBT parameters in realtime was achieved by adding several new registers (related to eCCA

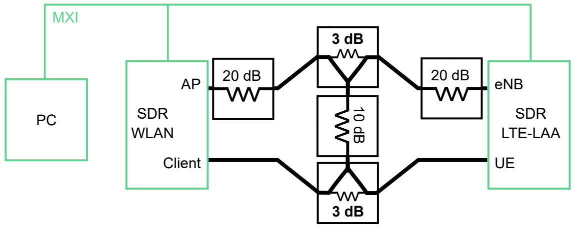

Fig. 3: Conducted SDR test setup for the LAA and WLAN system experiment (with two links).

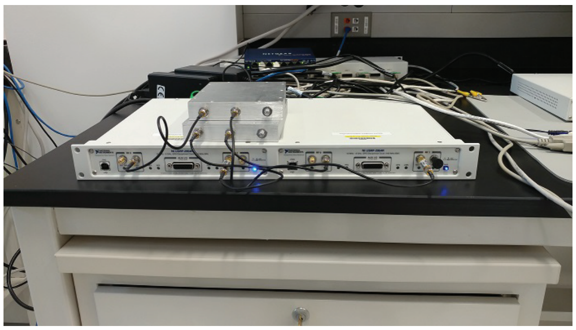

Fig. 4: Photo of part of the conducted SDR test setup.

and iCCA/DeCCA slot durations) to the FPGA code. These registers were also added to the FPGA-host interface.

The SDR software and devices we used had a significant LAA signal generation and transmission delay of about 50∼90 μs. This delay is defined as the duration starting from the instant that the LAA transmission decision is made until the instant that the LAA signal accesses the channel. Unfortunately, this delay can cause significant conflicts in channel access of LAA and WLAN nodes, and lead to increased collisions and degraded throughput. As a mitigation scheme, we added a new CRS generation function before the LAA signal transmission in FPGA code. This customized CRS is generated as soon as the LAA channel access decision is made, and transmitted with a negligible delay. This CRS has an adjustable duration in an host user-interface, and is seamlessly followed by the actual LAA signal transmission. This method basically solved the LAA transmission delay problem.

Finally, an automated testing interface was added to a host user-interface code that we wrote. This host code communicates via UDP with the commercial LAA and WLAN SDR codes that we modified with new FPGA functions. The modified LAA and WLAN codes accept and recognize automated commands and parameters and send back test results in realtime. These commands were not sent through the RF data link and did not cause overhead to the LAA and WLAN transmissions.

The WLAN implementation on the second SDR unit was achieved by use of commercially available software without additional FPGA programming. Additional changes were made to the host portion of the WLAN software, such as UDP-port communication and automated-testing modules. The WLAN communication link also used an RF loopback mode, similar to the case of LAA link. Only downlink WLAN traffic was simulated.

We modified the host software to allow online updating of several parameters in both LAA and WLAN links. The parameters include: transmit power, carrier frequency, ED threshold, throughput type, eCCA, mini-slot iCCA, and iCCA (or DeCCA) durations. However, during the measurements, only the eCCA duration was changed online.

During testing, the host SDR code sends commands to the SDR to update parameters at 0.5-second intervals, and receives test results from the SDR in one-second intervals. The result for each parameter setting is averaged over a specified number of received samples, such as 50. Then, the parameter of interest is updated. After requesting the next update, the software waits for ten seconds to allow the SDR devices to stabilize. Following the ten-second wait, the reading of the next set of samples begins.

This experimental setup enables the examination of coexistence theory and computer simulation in a highly controlled manner. Both the LTE and WLAN implementations used for conducted measurements are SDR representations designed for development purposes and are not commercially functioning networks.

IV. Experimental Results

In this section, we provide experimental results of the coexistence performance (Refer to Table I for values of some of the key parameters). We check the impact of two design features for LBT that may bring performance improvement for LAA links: subslot-tracking and anti-SJ. Note that the original LBT scheme includes neither the anti-SJ nor the subslot-tracking design.

We assume that the WLAN and LAA systems have channels fully overlapped with 20 MHz bandwidth at a center frequency 5.22 GHz in an ISM band. The LAA link uses modulation and coding scheme (MCS) 7 – quaternary phase-shift keying (QPSK) with rate 0.51, and the WLAN link uses QPSK with rate-1/2. When the transmission time efficiency is 100%, the physical layer channel bit rates (CBRs) are $\text{CBR}_L = 12.216$ Mbit/s for the LAA link, and $\text{CBR}_W = 12$ Mbit/s for the WLAN link. The LAA TXOP payload duration is given by $T_{P,L} = 2$ ms. The WLAN payload duration is computed by $T_{P,W} = 2048{\times}8/\text{CBR}_W = 1.4$ ms, where 2048 is the payload size in bytes per WLAN TXOP. The payload here may include physical layer headers and frame check sequence. The SDR-measured throughput for an LAA (or WLAN) link refers to correctly-decoded average data rate at receiver.

For the case of only one active LAA link (the WLAN link is not active), the baseline LAA throughput with Category-3 LBT is derived as

$$S_{L,only} = \frac{T_{p,L}\text{CBR}_L}{T_{p,L} + T_{\text{iCCA}} + \frac{Z_0-1}{2}\delta_L}, \quad (1)$$

where Z_0 is the LBT contention window (CW) size, and T_{iCCA} is the duration of initial CCA, set to be equal to LBT DeCCA duration and the WLAN DIFS duration (34 μs). Fig. 6 provides a comparison between the theoretical result in (1) and an SDR measurement result for the MCS-7 scheme when

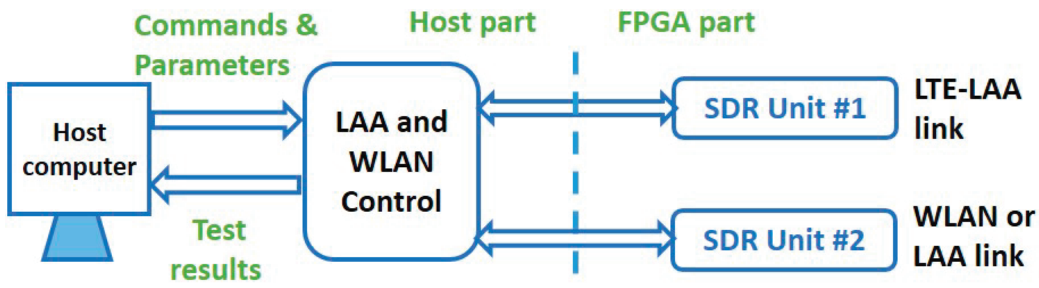

Fig. 5: Software control structure of the LAA and WLAN coexistence performance evaluation in conducted testings.

TABLE I: LTE-LAA and WLAN Parameters in Experimentation.

LAA parameters

Parameter	Value
Payload duration per transmission	2 ms
Transmit power	15 dBm
CCA ED threshold	-70 dBm
LBT defer period: T_{Defer} (=T_{DIFS})	34 μs
LBT eCCA period: T_{eCCA} (=$N_s\delta_W$)	$N_s \times 9$ μs
CW size Z_0	16

WLAN parameters

Parameter	Value
Payload duration per transmission	1.4 ms
Transmit power	10 dBm
CCA ED threshold	-72 dBm
T_{DIFS}	34 μs
Idle slot duration δ_W	9 μs
CW size W_0	16

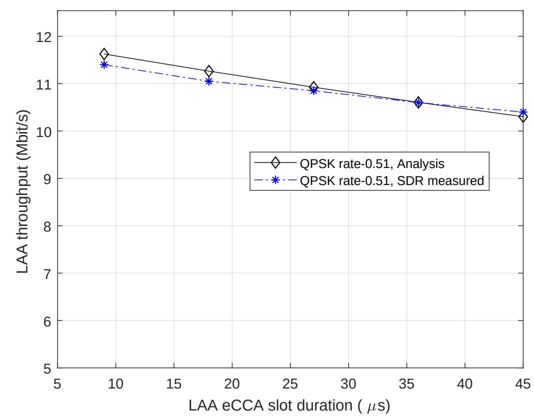

Fig. 6: Analytical and SDR-measured throughput of a single LTE-LAA link vs. eCCA slot duration.

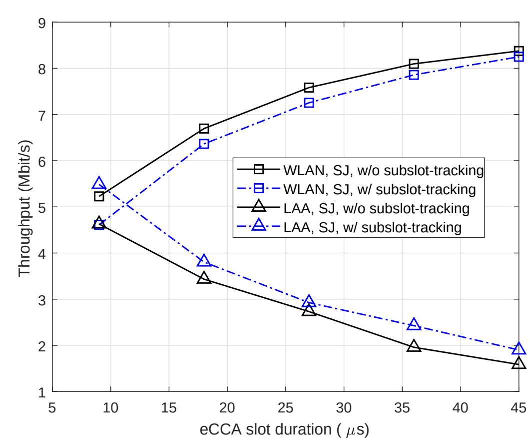

Fig. 7: SDR-measured throughput of the LAA with slot-jamming LBT and WLAN links vs. eCCA slot durations, either with or without subslot-tracking.

only the LAA link is active. A good match between analytical and measurement results is observed, with relative error of no more than 2%. We have also verified baseline throughput for one active 802.11 WLAN link (while the LAA link is not active) on an SDR device, which approximately matches with the result calculated by use of a method given in [21]. The detail is omitted here for brevity.

Next, we check two cases of LAA-based coexistence: one LAA link with one WLAN link (shown in Figs. 7 and 8), and two LAA links (shown in Fig. 9). In Fig. 7, we show the throughput of LAA (with the original SJ-LBT) and WLAN links. The WLAN idle slot duration is fixed at 9 μs. We observe that as the eCCA duration increases from 9 μs to 45 μs, the LAA throughput decreases while WLAN throughput increases significantly. Also, the LAA throughput is enhanced substantially by using our proposed subslot-tracking method compared to the original LBT which has no feature of subslot-tracking. For example, at $\delta_L = 9\mu s$, subslot-tracking brings about 0.9 Mbit/s enhancement to the LAA throughput than the case without it.

In Fig. 8, the throughput of LAA with the anti-SJ-LBT is provided. Comparison between Figs. 8 and 7 demonstrates that the anti-SJ-LBT provides a significantly higher throughput than the original SJ-LBT, either with or without subslot tracking. For example, with subslot-tracking, when $\delta_L = 45$ μs, the anti-SJ-LBT provides a throughput of about 3.2 Mbit/s and the

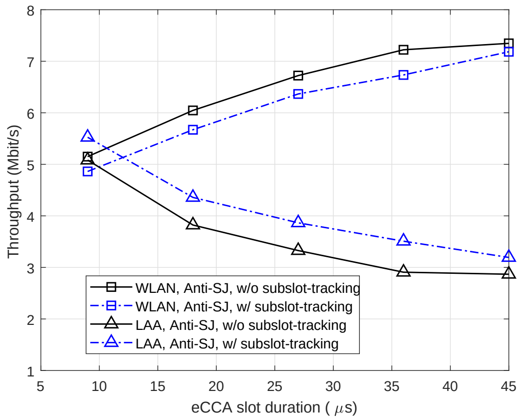

Fig. 8: SDR-measured throughput of the LAA with anti-slot-jamming LBT and WLAN links vs. eCCA slot durations, either with or without subslot-tracking.

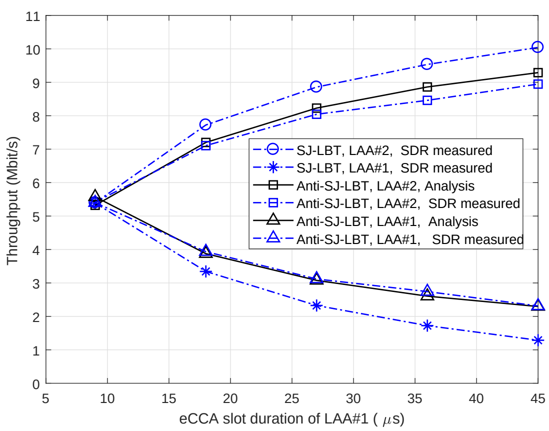

Fig. 9: Analytical and SDR-measured throughput of two LAA links with a fixed and a variable eCCA slot durations, respectively, with subslot-tracking.

original SJ-LBT has a throughput of about 2.0 Mbit/s. Results in Figs. 7 and 8 confirm the effectiveness of subslot-tracking and anti-SJ methods on enhancing the LAA throughput.

Finally, we show throughput of two LAA links in Fig. 9. Link #2 has a fixed eCCA duration (9 μs), and link #1 has a variable eCCA duration (from 9 μs to 45 μs), respectively. For the anti-SJ-LBT, both analytical result [17] and SDR measured result on LAA links are provided. The SJ-LBT scheme has not been analyzed, and only its SDR-measured result is provided. The result in Fig. 9 confirms an approximate match between the analysis given in [17] and SDR measurement result, and demonstrates the effectiveness of the anti-SJ design.

V. Conclusion

In this paper, we have described a slot boundary tracking error problem and a slot-jamming effect in the LTE-LAA LBT scheme, and provided an improved LBT design with subslot-tracking and anti-slot-jamming features. We have programmed the new LBT scheme in an FPGA, and implemented testing on coexisting LAA and WLAN links using SDR devices. Our developed testing method allows LBT parameters to be changed in realtime on the FPGA, and includes an automated testing procedure, which updates many system parameters in realtime. The results demonstrate the effectiveness of subslot-tracking and anti-SJ design methods, and confirm a reasonably good match between our analysis and experimental results. In future work, the effects of various fading channel models will be studied, and radiated testing will be implemented to further evaluate the coexistence performance of LAA-based systems.

References

[1] 3GPP TSG RAN, "Study On Licensed-Assisted Access To Unlicensed Spectrum", 3GPP TR 36.889 V13.0.0, Jun. 2015.

[2] Ericsson, "Discussion on LBT protocols," 3GPP Tech. Rep. R1-151996, Apr. 2015.

[3] LTE-U Forum, "Coexistence study for LTE-U SDL", LTE-U Technical Report, V1.0, Feb. 2015.

[4] R. Zhang, M. Wang, L. X. Cai, Z. Zheng, and X. Shen, "LTE-unlicensed: the future of spectrum aggregation for cellular networks," *IEEE Wireless Commun.*, vol. 22, no. 3, pp. 150–159, Jun. 2015.

[5] T. Tao, F. Han and Y. Liu, "Enhanced LBT algorithm for LTE-LAA in unlicensed band," in *Proc. IEEE PIMRC,* Hong Kong, 2015, pp. 1907-1911.

[6] A. Bazzi, B. M. Masini and A. Zanella, "Performance analysis of V2V beaconing using LTE in direct mode with full duplex radios," *IEEE Wireless Commun. Lett.*, vol. 4, no. 6, pp. 685-688, Dec. 2015.

[7] I. Gomez-Miguelez, et al., "srsLTE: An Open-source Platform for LTE Evolution and Experimentation," in *Proc. 10th ACM WiNTECH*, New York, 2016, pp. 25–32.

[8] B. Kouassi et al., "Design and implementation of spatial interweave LTE-TDD cognitive radio communication on an experimental platform," *IEEE Wireless Commun.*, vol. 20, no. 2, pp. 60-67, April 2013.

[9] V. Marojevic, D. Chheda, R. M. Rao, R. Nealy, J. Park, and J. Reed, "Software-defined LTE evolution testbed enabling rapid prototyping and controlled experimentation," in *Proc. IEEE WCNC*, San Francisco, USA, Mar. 2017.

[10] S. Bhattarai, J. Park, B. Gao, K. Bian, and W. Lehr, "An overview of dynamic spectrum sharing: ongoing initiatives, challenges, and a roadmap for future research," *IEEE Trans. Cognitive Commun. Net.*, Vol. 2, No. 2, June 2016, pp. 110-128.

[11] A. Mukherjee et al., "Licensed-assisted access LTE: coexistence with IEEE 802.11 and the evolution toward 5G," *IEEE Commun. Mag.*, vol. 54, no. 6, pp. 50-57, Jun. 2016.

[12] National Instrument Inc. white paper, "Real-time LTE/Wi-Fi Coexistence Testbed," Feb. 16, 2016. Available: http://www.ni.com/white-paper/53044/en/

[13] IEEE LAN/MAN Standards Committee, IEEE Std 802.11-2012, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Feb. 2012.

[14] C. Chen, R. Ratasuk, and A. Ghosh, "Downlink performance analysis of LTE and WiFi coexistence in unlicensed bands with a simple listen-before-talk scheme," in *Proc. IEEE VTC*, May 2015, pp. 1–5.

[15] Y. Song, K. W. Sung, and Y. Han, "Coexistence of Wi-Fi and cellular with listen-before-talk in unlicensed spectrum," *IEEE Commun. Lett.*, vol. 20, no. 1, pp. 161–164, Jan. 2016.

[16] Y. Ma and D. G. Kuester, "MAC-Layer coexistence analysis of LTE and WLAN systems via listen-before-talk," in *Proc. IEEE CCNC*, Las Vegas, USA, Jan. 2017.

[17] Y. Ma, D. G. Kuester, J. Coder and W. Young, "Coexistence analysis of LTE and WLAN systems with heterogenous backoff slot durations," in *Proc. IEEE ICC*, Paris, France, 2017, pp. 1-7.

[18] S. Han, Y. C. Liang, Q. Chen and B. H. Soong, "Licensed-assisted access for LTE in unlicensed spectrum: A MAC protocol design," in *Proc. IEEE ICC*, 2016, pp. 1–6.

[19] R. Yin, G. Yu, A. Maaref, and G. Y. Li, "A framework for co-channel interference and collision probability tradeoff in LTE licensed-assisted access networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 9, pp. 6078–6090, Sept. 2016.

[20] Y. Gao, X. Sun and L. Dai, "IEEE 802.11e Std EDCA networks: modeling, differentiation and optimization," *IEEE Trans. Wireless Commun.*, vol. 13, no. 7, pp. 3863–3879, July 2014.

[21] J. Jun, P. Peddabachagari, and M. Sichitiu, "Theoretical Maximum Throughput of IEEE 802.11 and its Applications," in *Proc. IEEE NCA*, 2003.